[0008] When an electric potential is applied between an anode and cathode, the conductive material of the anode covering the reservoir oxidizes to form soluble compounds or ions that dissolve into solution, exposing the molecules to be delivered to the surrounding fluids. Alternatively, the application of an electric potential can be used to create changes in local pH near the anode reservoir cap to allow normally insoluble ions or oxidation products to become soluble. This allows the reservoir cap to dissolve and to expose the molecules to be released to the surrounding fluids. In either case, the molecules to be delivered are released into the surrounding fluids by diffusion out of or by degradation or dissolution of the release system. The frequency of release is controlled by incorporation of a miniaturized power source and microprocessor onto the microchip.

[0009] One solution to achieving biocompatibility, impermeability, and galvanic and electrolytic compatibility for an implanted device is to encase the device in a protective environment. It is well known to encase implantable devices with glass or with a case of ceramic or metal. Schulman, et al. (U.S. Pat. No. 5,750,926) is one example of this technique. It is also known to use alumina as a case material for an implanted device as disclosed in U.S. Pat. No. 4,991,582. Santini, et.al. (U.S. Pat. No. 6,123,861) discuss the technique of encapsulating a non-biocompatible material in a biocompatible material, such as poly(ethylene glycol) or polytetrafluoroethylene-like materials. They also disclose the use of silicon as a strong, non-degradable, easily etched substrate that is impermeable to the molecules to be delivered and to the surrounding living tissue. The use of silicon allows the well-developed fabrication techniques from the electronic microcircuit industry to be applied to these substrates. It is well known, however, that silicon is dissolved when implanted in living tissue or in saline solution.

Summary of the Invention

[0010] An implantable microfluidic delivery system is coated with a thin film coating, about one-micron thick, of ultra-nanocrystalline diamond; thereby assuring that the device is biocompatible and impermeably sealed. The impermeable seal prevents the substrate from dissolving due to contact with living tissue. The conformal ultra-nanocrystalline diamond coating uniformly covers the device, providing relief from sharp edges and producing a strong, uniformly thick impermeable coating around sharp edges and on high aspect-ratio parts. The conformal nature of the coating helps assure impermeability and strength despite the presence of difficult to coat shapes.

[0011] When employed as an ultra-nanocrystalline diamond cover on the drug-containing reservoir, the coating may be designed to be removable by application of an electric current. The coating is selectively patterned by doping to create electrically conductive areas that are used as an electrically activated release mechanism for drug delivery and that are electrical conductors which carry electric current to electrodes to initiate the electrically activated release mechanism

OBJECTS OF THE INVENTION

[0012] It is an object of the invention to provide an ultra-nanocrystalline diamond coated microchip drug delivery substrate that is impermeably sealed and inert for implantation in a living body.

[0013] It is an object of the invention to provide an ultra-nanocrystalline diamond coated microchip drug delivery substrate that has a uniform thickness coating around corners such that the coating maintains its impermeable sealing capability.

[0014] It is an object of the invention to provide an ultra-nanocrystalline diamond coated microchip drug delivery substrate that has electrically conductive areas that are patterned to provide a mechanism for electrically activated drug release.

[0015] Other objects, advantages and novel features of the present invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawing.

Brief Description of the Drawings

[0016] FIG. 1 illustrates a perspective view of the microchip drug delivery device.

Detailed Description of the Preferred Embodiments

[0017] Implantable microchip fluid delivery devices generally are comprised of a microchip 1, as shown in FIG. 1. The microchip 1 must be biocompatible and impermeable to assure that the drug or other molecule 5 contained in the reservoirs of the substrate 3 are protected from the living tissue of the body and to retain the drug or other molecule 5 until the desired release time.

[0018] It is known to fabricate reservoirs, by conventional microchip techniques, in the substrate of the delivery device from silicon. Silicon is dissolved when exposed, long term, to living tissue in a living body, unless coated with a biocompatible coating. An ultra-nanocrystalline diamond (UNCD) coating13 exhibits excellent mechanical. electrical, and electrochemical properties. Using a thin film coating deposition process, such as that disclosed by Gruen and Krauss (U.S. Pat. No. 5,772,760), yields a coating that is inherently low in porosity, electrically non-conductive and biocompatible. U.S. Pat. No. 5,772,760 is incorporated herein by reference in its entirety. Coatings as thin as 40 nm have demonstrated excellent impermeability properties. The UNCD thin film coating13 is conformal when applied to complex or high aspect-ratio shapes.

[0019] Characteristics of this UNCD coating 13 that make it particularly well suited to the present invention are:

[0020] uniform morphology resulting in a very high bulk density,

[0021] highly conformal and able to cover very high-aspect ratio features uniformly,

[0022] electrical properties can be controlled by varying the deposition parameters, so as to make selected areas electrically conductivity.

[0023] low-temperature deposition thereby avoiding damage to electrical and passive components, and

[0024] easily patternable via selective seeding, photolithography, or oxygen etching.

[0025] Unique UNCD coating 13 properties are not all present in any other single coating candidate for microchip drug delivery devices. Candidate coatings include conventional chemical vapor deposited diamond thin films, diamond-like carbon, or SiC. However, none of these coatings offers impermeability in thin coatings that are applied at low temperature and that are deposited by a none-line-of-sight method, as does UNCD. The UNCD coating 13 possesses these characteristics:

[0026] (a) extremely low surface roughness (20-30 nm), approximately independent of film thickness up to approximately 10 μm thickness;

[0027] (b) extremely good conformality when deposited on high aspect-ratio features;

[0028] (c) extremely low coefficient of friction;

[0029] (d) high hardness, fracture toughness, flexural strength, and wear life,

[0030] (e) low electrical conductivity, but can be doped to become conductive, and

[0031] (f) excellent resistant to degradation in living tissue environments.

[0032] The UNCD coating 13 consists primarily of phase pure randomly oriented diamond crystallites. UNCD coatings are grown using a microwave plasma chemical vapor deposition technique involving a C_{60}/Ar or CH_4/Ar chemistry, which provides C_2 dimers as the main growth species that insert directly into the growing diamond lattice with a low energy barrier. The limited amount of atomic hydrogen in the plasma leads to a very high re-nucleation rate (~10^{11} cm^{-2} sec^{-1}). This results in the UNCD coatings 13 with 2 to 5 nm grain size and 0.4 nm grain boundaries that provide the unique properties described herein. In addition, the low activation energy for C_2 species incorporation into the growing film yields the UNCD coating 13 at temperatures as low as approximately 350° C. This temperature is very low compared to many conventional coating processes, such as glass encapsulation or chemical vapor deposition.

[0033] Miniaturized drug delivery devices that are implanted in a living body benefit from a UNCD coating 13 that, in addition to biocompatibility, corrosion resistance, and impermeability, can be patterned to form electrically conductive electrodes. Patterning is done by selective doping of the UNCD coating 13 to convert the normally electrically insulating UNCD 13 to an electrical conductor. The electrical conductors 11 are formed in this manner, as is the anode electrode reservoir cap 9. These electrode caps 9 are formed as covers on the drug 5 or other molecule-containing reservoirs. Upon application of an electric current along the electrical conductors 11, through the cathode electrodes 7 and into the anode electrode reservoir cap 9 anode electrode reservoir cap 9 disintegrates to expose the drug or other molecule 5 to the living tissue, thus allowing the drug or other molecule 5 to enter the body. It is obvious that the device may equally well be used to deliver reagents or to act as a diagnostic agent in addition to delivering drugs.

[0034] The inert nature of a very thin coating of UNCD 13 was demonstrated by the present inventors. A silicon substrate coated with 40 nm of UNCD coating 13 was exposed to silicon etchant having a composition of 67% HNO_3 and 33% HF, by volume. The etchant was placed drop-wise on the UNCD coating 13, where it was allowed to stand at 60° C for one-hour. The coating had been unaffected when observed microscopically at 1000x after this exposure.

[0035] Therefore, the UNCD coating 13 may be used as part of a biocompatible and impermeable microchip drug delivery packaging process to isolate the substrate 3, which is typically silicon, and to isolate the drug or other molecule 5 from the tissue and fluids that are present in the living tissue. In this manner, the substrate 3 is protected from attack by the living tissue and the drug or other molecule 5 is maintained free from attack by either the silicon or the living tissue.

[0036] The UNCD coating 13 on an integrated circuit is “conformal”, which means that the coating has a uniform thickness as the coating follows the contours of the device. Achieving a conformal coating on high aspect-ratio

parts and around sharp corners on these devices is a particular challenge for thin films that are deposited by other means. UNCD coating 13 uniformly covers all aspects of the intricately machined substrate 3 including the multiplicity of reservoirs.

[0037] Obviously, many modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.